Generation of GHZ-type and W-type entangled coherent states of three-cavity fields

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We present experimental schemes to prepare the three-cavity GHZ-type and W-type entangled coherent states in the context of dispersive cavity quantum electrodynamics. The schemes can be easily generalized to prepare the GHZ-type and W-type entangled coherent states of n-cavity fields. The discussion of our schemes indicates that it can be realized by current technologies.

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Quantum entanglement is at the heart of quantum information science and technology. Information may be coded on quantum two-level systems ("qubits") [1]. Nonlocal correlations between two qubits can be used for quantum key distribution [2] or quantum teleportation [3]. More complex entanglement manipulations could be used for quantum error correction [4] or entanglement purification [5]. The preparation of complex quantum entangled states in well-controlled conditions is the subject of an intense experimental activities. Complex entangled states, such as Greenberger-Horne-Zeilinger (GHZ) [6] class and the W [7] class, can be used to understand basic quantum phenomena and can also be used for information processing. Recently, many schemes have been proposed for generating GHZ states [8], and W states [9].

Entanglement in continuous variables has been of great interest since the celebrated paper of Einstein, Podolsky and Rosen (EPR) [10] who constructed a two-particle state which was strongly entangled both in position and momentum spaces. The so-called continuous-variable quantum information is that quantum information can be coded in a state which is characterized by infinite number of degrees of freedom, such as a position or momentum wave function of a microscopic particle or the quadrature components of a field. The continuous-variable approach promises to be more compact and more efficient in both coding and manipulating quantum information and thus has been developed rapidly during the last few years from both theoretical and experimental point of view [11]. An intermediate, quite simple but very useful, way for coding is to utilize superpositions of a finite number of macroscopically distinguishable states each of which is however embedded in an unbounded vector space [12]. In this approach, instead of qubits, one deals with logical qubits. A logical qubit is regarded as a superposition of two continuous-variable states which are linearly independent but not necessarily orthogonal to each other. An elegant choice for representing logical qubit is to use two coherent states $|\alpha\rangle$ and $|-\alpha\rangle$ of an optical mode, with α the complex coherent amplitude. A coherent field is a fundamental tool in quantum optics and linear superposition of two coherent states is considered one of the realizable mesoscopic quantum systems [13]. To process quantum information encoded in logical qubits, recently, Nguyen [14] firstly proposed GHZ-type and W-type entangled coherent states (ECSs). The so-called GHZ-type ECS is

$$
\begin{aligned}
|\mathtt{GHZ},\alpha\rangle_{1\ldots N} = c_1|\alpha,\alpha,\ldots,\alpha\rangle_{1\ldots N} \\
+c_2|-\alpha,-\alpha,\ldots,-\alpha\rangle_{1\ldots N},
\end{aligned}
\tag{1}
$$

where $c_{1,2}$ the normalization coefficients, and the W-type ECS is

$$
\begin{aligned}
|W,\alpha\rangle_{1\ldots N} = b_1|\alpha,-\alpha,\ldots,-\alpha\rangle_{1\ldots N} \\
+b_2|-\alpha,\alpha,\ldots,-\alpha\rangle_{1\ldots N} + \ldots \\
+b_N|-\alpha,-\alpha,\ldots,\alpha\rangle_{1\ldots N},
\end{aligned}
\tag{2}
$$

where b_i $(i = 1, 2, \ldots, N)$ the normalization coefficients [14]. Since the amount of entanglement in Eq. (1) and Eq. (2) is independent of $|\alpha\rangle$, it may seem that such states may be especially robust against decoherence due to photon absorption. Namely, although photon absorption attenuates the coherent state, that by itself has no effect on the entanglement.

In this paper, we propose schemes to generate the GHZ-type and W-type ECSs of three-cavity fields. Some theoretical schemes have been proposed [15, 16] to generate GHZ-type ECS, especially, Gerry [15] proposed an elegant scheme to generate GHZ-type ECS of three cavities using a Ξ-type three-level atom with three separated cavities, but there is no report of experimental realization of the GHZ-type ECS state. Here, we present an alternative, and feasible scheme to generate GHZ-type ECS with current cavity QED technology. To our best knowledge, our scheme here is the first one for generating W-type ECS. Our schemes are based on the present cavity quantum electrodynamics (QED) techniques. Cavity QED, with Rydberg atoms crossing superconducting cavities, offers an almost ideal system for the generation of entangled states and implementation of small scale quantum information processing.

We consider a system composed of a single two-level atom and a single-mode cavity field. The atom-field interaction is described by the Jaynes-Cummings model. In the rotating-wave approximation, the Hamiltonian of

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the system is given by (assuming $\hbar = 1$) [17]

$$H = H_0 + H_I, \tag{3}$$

$$H_0 = \omega a^\dagger a + \frac{1}{2}\omega_0 \sigma_Z, \tag{4}$$

$$H_I = g(a^\dagger \sigma^- + a\sigma^+), \tag{5}$$

where $\sigma^+ = |e\rangle\langle g|$, $\sigma^- = |g\rangle\langle e|$, and $\sigma_z = |e\rangle\langle e| - |g\rangle\langle g|$. $a^\dagger$ (a) is the creation (annihilation) operator of the cavity field. ω_0 and ω are the atomic transition frequency and the cavity field frequency, respectively, and g is the atom-field coupling constant.

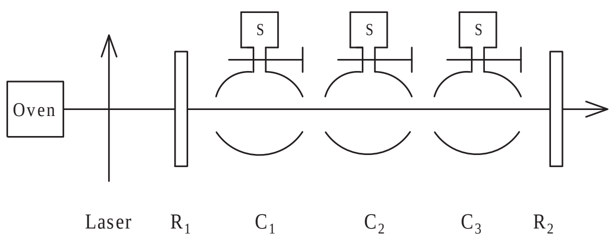

FIG. 1: Experimental setup for generation of three-cavity GHZ-type entangled coherent state. C_1, C_2, and C_3 are identical cavities. R_1 and R_2 are the Ramsey zones. S is a classical source of microwaves which are injected into the cavity through a waveguide.

If the detuning between the atomic transition frequency and the cavity field frequency is much larger than the coupling constant, the atom has a negligible probability of making a transition between the ground and excited states. Under this condition, the effective interaction Hamiltonian can be written as [18]

$$H_{eff} = \lambda a^\dagger a \sigma_z, \tag{6}$$

where $\lambda = \frac{g^2}{\delta}$, $\delta = \omega_0 - \omega$. In the interaction picture, the evolution of the whole system is $|\psi(t)\rangle = e^{-iH_{eff}t}|\psi(0)\rangle$ ($[H_{eff}, H_0] = 0$), where $|\psi(0)\rangle$ is the initial state of the whole system. If the atom is initially in the excited state or in the ground state and the cavity field is initially in the coherent state $|\alpha\rangle$, then after the interaction time τ , the process from the initial state of the atom-field system to the final state can be written as

$$|e\rangle|\alpha\rangle \rightarrow |e\rangle|\alpha e^{-i\lambda\tau}\rangle, \tag{7}$$

or

$$|g\rangle|\alpha\rangle \rightarrow |g\rangle|\alpha e^{i\lambda\tau}\rangle. \tag{8}$$

Firstly, we describe the process of preparing the GHZ-type three-cavity ECS. The experimental setup for the proposed method is shown in Fig. 1. The three identical cavities C_1, C_2, C_3 are prepared in the coherent state $|\alpha\rangle_1$, $|\alpha\rangle_2$, $|\alpha\rangle_3$ by injection of classical microwave fields. Subsequently a Rydberg atom is initially prepared in the superposition $(|e\rangle + |g\rangle)/\sqrt{2}$ by laser excitation to state $|e\rangle$ followed by a $\pi/2$ pulse of classical microwave radiation in the first Ramsey zone R_1. The $\pi/2$ pulses of the Ramsey zones effect the transformations $|e\rangle \rightarrow |e\rangle + |g\rangle$, $|g\rangle \rightarrow |g\rangle - |e\rangle$. Thus as the atom enters the cavity, the initial atom-field state is

$$|\psi(0)\rangle = \frac{1}{\sqrt{2}}(|e\rangle + |g\rangle)|\alpha\rangle_1|\alpha\rangle_2|\alpha\rangle_3. \tag{9}$$

Just as the atom leaves the cavity C_1, the state of the system is

$$|\psi(t_1)\rangle = \frac{1}{\sqrt{2}}[|e\rangle|\alpha e^{-i\theta_1}\rangle_1 + |g\rangle|\alpha e^{i\theta_1}\rangle_1]|\alpha\rangle_2|\alpha\rangle_3, \tag{10}$$

where $\theta_1 = \lambda t_1$, t_1 is the transit time of the atom across the cavity C_1. Just as the atom leaves the cavity C_2, the state of the system is

$$\begin{aligned} |\psi(t_1+t_2)\rangle = \frac{1}{\sqrt{2}}[&|e\rangle|\alpha e^{-i\theta_1}\rangle_1|\alpha e^{-i\theta_2}\rangle_2 \\ &+|g\rangle|\alpha e^{i\theta_1}\rangle_1|\alpha e^{i\theta_2}\rangle_2]|\alpha\rangle_3, \end{aligned} \tag{11}$$

where $\theta_2 = \lambda t_2$, t_2 is the transit time of the atom across the cavity C_2. After the atom leaves the cavity C_3, the state of the system

$$\begin{aligned} |\psi(t_1+t_2+t_3)\rangle = \tfrac{1}{\sqrt{2}}[&|e\rangle|\alpha e^{-i\theta_1}\rangle_1|\alpha e^{-i\theta_2}\rangle_2|\alpha e^{-i\theta_3}\rangle_3 \\ &+|g\rangle|\alpha e^{i\theta_1}\rangle_1|\alpha e^{i\theta_2}\rangle_2|\alpha e^{i\theta_3}\rangle_3], \end{aligned} \tag{12}$$

where $\theta_3 = \lambda t_3$, t_3 is the transit time of the atom across the cavity C_3. Since the three cavities are identical, it is reasonable to assume that $t_1 = t_2 = t_3 = t$, and therefore $\theta_1 = \theta_2 = \theta_3 = \theta$. The atom is velocity selected such that $\theta = \pi/2$. After the atom leaves the cavity C_3, the

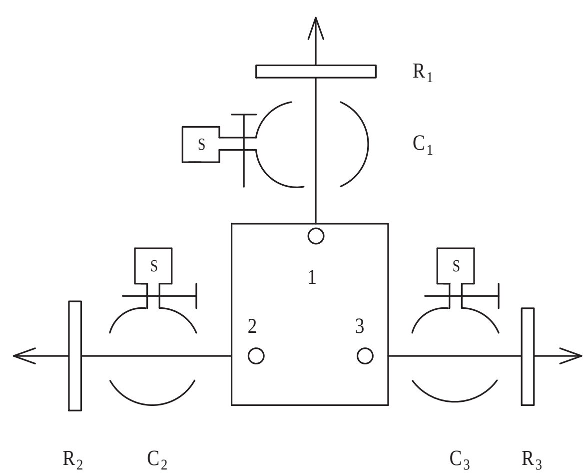

FIG. 2: Experimental setup for generation of three-cavity W-type entangled coherent state. C_1, C_2, and C_3 are identical cavities. R_1, R_2 and R_3 are the Ramsey zones. Atoms 1, 2, 3 are initially in W state $|W\rangle = \frac{1}{\sqrt{3}}(|egg\rangle + |geg\rangle + |gge\rangle)$. S is a classical source of microwaves which are injected into the cavity through a waveguide.

Ramsey zone R_2 applies a $\pi/2$ pulse to give

$$\begin{aligned}|\psi^{'}(3t)\rangle &= N_0\{|g\rangle[|\beta\rangle_1|\beta\rangle_2|\beta\rangle_3+|-\beta\rangle_1|-\beta\rangle_2|-\beta\rangle_3] \\ &-|e\rangle[|\beta\rangle_1|\beta\rangle_2|\beta\rangle_3-|-\beta\rangle_1|-\beta\rangle_2|-\beta\rangle_3]\},\end{aligned} \tag{13}$$

where $\beta=\alpha e^{-i\theta}$, and N_0 is the normalization factor. If the atom is subsequently selectively ionized and found to be in the ground state $|g\rangle$ or excited state $|e\rangle$, then the three-cavity field is respectively projected onto the state

$$|\beta\rangle_1|\beta\rangle_2|\beta\rangle_3+|-\beta\rangle_1|-\beta\rangle_2|-\beta\rangle_3, \tag{14}$$

or the state

$$|\beta\rangle_1|\beta\rangle_2|\beta\rangle_3-|-\beta\rangle_1|-\beta\rangle_2|-\beta\rangle_3, \tag{15}$$

which are just the so-called GHZ-type ECSs.

Next, let us discuss how to prepare three-cavity W-type ECS. The experimental setup is shown in Fig. 2. Assuming three identical cavities C_1, C_2 and C_3 are initially in coherent states $|\alpha_1\rangle$, $|\alpha_2\rangle$ and $|\alpha_3\rangle$ by injection of classical microwave fields, respectively. Atoms 1, 2, and 3 share an W state, i.e. $|W\rangle_{123}=\frac{1}{\sqrt{3}}(|egg\rangle+|geg\rangle+|gge\rangle)$. Firstly, we send atoms 1, 2 and 3 at the same velocity, which will go through cavities C_1, C_2 and C_3, respectively. The initial state of the three atoms and the three-cavity fields is

$$|\Psi(0)\rangle=\frac{1}{\sqrt{3}}[|egg\rangle+|geg\rangle+|gge\rangle]|\alpha\rangle_1|\alpha\rangle_2|\alpha\rangle_3. \tag{16}$$

After the three atoms leave their respective cavities, the state of the whole system is

$$\begin{aligned}|\Psi(\tau)\rangle = \frac{1}{\sqrt{3}}[&|egg\rangle|\alpha e^{-i\theta}\rangle_1|\alpha e^{i\theta}\rangle_2|\alpha e^{i\theta}\rangle_3 \\ &+|geg\rangle|\alpha e^{i\theta}\rangle_1|\alpha e^{-i\theta}\rangle_2|\alpha e^{i\theta}\rangle_3 \\ &+|gge\rangle|\alpha e^{i\theta}\rangle_1|\alpha e^{i\theta}\rangle_2|\alpha e^{-i\theta}\rangle_3],\end{aligned} \tag{17}$$

where $\theta=\lambda\tau$, τ is the transit time of the three atoms across the cavities, respectively. (We assume the transit times of the three atom are equal.) After the three atoms 1, 2, and 3 leave their respective cavities, they enter three Ramsey zones R_1, R_2, R_3, respectively. The three Ramsey zones apply $\pi/2$ pulses to give

$$\begin{aligned}|\Psi^{'}(\tau)\rangle = N_e[&(|egg\rangle_{123}-|eeg\rangle_{123}+|ggg\rangle_{123}-|geg\rangle_{123} \\ &-|ege\rangle_{123}+|eee\rangle_{123}-|gge\rangle_{123} \\ &+|gee\rangle_{123})|\alpha e^{-i\theta}\rangle_1|\alpha e^{i\theta}\rangle_2|\alpha e^{i\theta}\rangle_3 \\ &+(|geg\rangle_{123}-|eeg\rangle_{123}+|ggg\rangle_{123}-|egg\rangle_{123}-|gee\rangle_{123} \\ &+|eee\rangle_{123}-|gge\rangle_{123}+|ege\rangle_{123})|\alpha e^{i\theta}\rangle_1|\alpha e^{-i\theta}\rangle_2|\alpha e^{i\theta}\rangle_3 \\ &+(|ggg\rangle_{123}-|geg\rangle_{123}-|egg\rangle_{123}+|eeg\rangle_{123}+|gge\rangle_{123} \\ &+|eee\rangle_{123}-|ege\rangle_{123}-|gee\rangle_{123})|\alpha e^{i\theta}\rangle_1|\alpha e^{i\theta}\rangle_2|\alpha e^{-i\theta}\rangle_3],\end{aligned} \tag{18}$$

where N_e is the normalization factor. We assume that the atom is velocity selected such that $\theta=\pi/2$. Introducing $\beta=\alpha e^{-i\theta}$, Eq. (18) can be rewritten as

$$\begin{aligned}|\Psi^{'}(\tau)\rangle = N_e[&(|ggg\rangle_{123}+|eee\rangle_{123})(|-\beta\rangle_1|\beta\rangle_2|\beta\rangle_3+|\beta\rangle_1|-\beta\rangle_2|\beta\rangle_3+|\beta\rangle_1|\beta\rangle_2|-\beta\rangle_3) \\ &-(|gge\rangle_{123}+|eeg\rangle_{123})(|-\beta\rangle_1|\beta\rangle_2|\beta\rangle_3+|\beta\rangle_1|-\beta\rangle_2|\beta\rangle_3-|\beta\rangle_1|\beta\rangle_2|-\beta\rangle_3) \\ &+(|egg\rangle_{123}+|gee\rangle_{123})(|-\beta\rangle_1|\beta\rangle_2|\beta\rangle_3-|\beta\rangle_1|-\beta\rangle_2|\beta\rangle_3-|\beta\rangle_1|\beta\rangle_2|-\beta\rangle_3) \\ &-(|geg\rangle_{123}+|ege\rangle_{123})(|-\beta\rangle_1|\beta\rangle_2|\beta\rangle_3-|\beta\rangle_1|-\beta\rangle_2|\beta\rangle_3+|\beta\rangle_1|\beta\rangle_2|-\beta\rangle_3)].\end{aligned} \tag{19}$$

After the three atoms 1, 2 and 3 exit from their respective cavities, their final states are analyzed in the state-selective field-ionization detectors, respectively. Depending on the detection results of the atomic states, the three-cavity fields are projected onto one of the four W-type ECSs in Eq. (19).

In order to realize the suggested schemes, it is necessary to discuss dissipative process due to cavity losses and atomic spontaneous emission. However, we consider Rydberg atoms of long radiative lifetime and high-Q superconducting microwave cavities, the atom-field interactions dominate the dissipative processes. According to Ref. [19], for Rydberg atoms in circular states with principal quantum numbers 50 and 51 (transition frequency $\nu_0\sim 51$ GHz), the atomic radiative lifetime T_{at} can reach 30 ms and the cavity lifetime can be $T_r=1$ ms (corresponding to $Q=3\times10^8$). The length of the cavity is of the order of centimeter and the velocity of the atom is of the order of 100 m/s, so the transit time of the atom in the cavity is about 0.1 ms. This transit time is much shorter than the atomic radiative lifetime T_{at} and the cavity lifetime T_r, therefore, the decoherence due to cavity losses and atomic spontaneous emission can be ignored. Consequently, the GHZ-type and W-type ECSs of three-cavity fields can be generated.

In conclusion, we have proposed schemes for preparing the GHZ-type and W-type ECSs of three-cavity fields, and they can be realized experimentally based on current cavity QED technique. Furthermore, our schemes can be easily generalized to the preparation of the GHZ-type

and W-type ECSs of n-cavity fields ($n \geq 3$).

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